A Critical Examination of the Einstein Eclipse Tests by Professor A. D. Ross, M.A., D.Sc., F.R.S.E.

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From his restricted theory of relativity, Einstein in 1911 predicted * that stars observed in the field surrounding the totally eclipsed sun should be displaced outwards by an amount $0 \cdot 83$sec./d, where d is the angular distance of the star from the sun's centre expressed in terms of the sun's radius. The value was corrected later to $0 \cdot 87$sec./d. The generalised theory † increased the amount of the deviation to $1 \cdot 745$sec./d, being double the value which would follow from a simple hypothesis that the mass of the electro-magnetic energy of light is subject to gravitation. ‡

Attempts to apply this crucial test of Einstein's theory were made at the following eclipses :—1914, August 21 (Russia) ; 1918, June 8 (U.S.A.) ; 1919, May 29 (Brazil and Africa) ; 1922, September 21 (Australia and Christmas Island) ; 1923, September 10 (U.S.A. and Mexico).

In 1914 the Lick Observatory expedition failed through cloudy weather, while the Babelsberg expedition was withdrawn owing to the outbreak of war. The 4-inch 15-ft. lenses used by the Lick party in 1918 unfortunately did not give a sufficiently flat field, and the measures of the plates were altogether inconclusive. The mean of the measurements seemed if anything to support the half deflection.§

In 1910 two British expeditions made observations at Sobral in Brazil and at Principe Island in the Gulf of Guinea. The results (expressed in seconds of arc) were ‖ :—

Station.	Instrument.	Plates.	Stars.	Result.	Probable Error.
Sobral	Astrograph	18	6 to 12	$0 \cdot 86$	?
,, ...	,,	18	5	$0 \cdot 93$	?
,, ...	4-inch lens	7	7	$1 \cdot 98$	$0 \cdot 12$
Principe	Astrograph	16	4 to 5	$1 \cdot 61$	$0 \cdot 30$

The British astronomers considered that the probable errors calculated from the deviations of individual observations from the mean did not in all cases represent the whole uncertainty.

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* A. Einstein, Ann. d. Physik, xxxv., p. 898 (1911).
† A. Einstein, Ann. d. Physik, xlix., p. 769 (1916).
‡ A. D. Ross, Proc. Roy. Soc. W.A., v., p. 93 (1920).
§ W. W. Campbell, Observatory, xlii., p. 298 (1919).
‖ F. W. Dyson, A. S. Eddington, C. Davidson, Memoirs R.A.S., lxii., Appendix (1920) ; Phil. Trans. Roy. Soc., A. ccxx., p. 291 (1920).

Systematic errors were probably introduced through distortion of the coelostat mirror *, and imperfection of the star images diminished the value of the Sobral astrographic measures. On the whole the tests favoured the Einstein prediction. †

In 1922 observations were made by the Lick Observatory, Toronto University, and Kodaikanal Observatory expeditions at Wallal, W.A., by the Adelaide Observatory expedition at Cordillo Downs, S.A., and by the Sydney Observatory party at Goondiwindi, Queensland. The Adelaide Observatory plates have been forwarded to the Royal Observatory, Greenwich, for measurement, and the work is still in progress. The Kodaikanal ‡ and Sydney attempts have been abandoned owing to the photographs taken having proved unsatisfactory.

The Canadian party under Professor Chant obtained two eclipse photographs $E1$ and $E2$ with an 11-ft. camera working at $f22$ §. Comparison plates $N1$ and $N2$ of the eclipse field were taken by Dr. Trumpler in May, 1922, at Tahiti, with the same camera, and also an "intermediate plate" M of the same region photographed through the glass, the film side of the plate in the holder being turned away from the lens. Hence plate M could be superimposed on any of the plates $E1$, $E2$, $N1$, $N2$, film to film, with corresponding stellar images in close proximity. The images on M were thus used as "intermediates" to compare the positions on $E1$ and $N1$ or $E2$ and $N2$. Lateral and rotational displacements of one plate relative to the other, and differences in scale value (due to change in focal length of the camera) all result in apparent displacements of the stars under different laws to the Einstein effect, and these effects could thus be eliminated ‖. Allowance was made for differential refraction and aberration, and then, assuming the existence of the Einstein term, its value at the sun's limb was deduced by the method of least squares from the resultant equations. About 25 stellar images were obtained, but only 19 were subjected to measurement. The measurements of one star were omitted from the computations as altogether unsatisfactory, and of the 18 others, three gave results which were evidently considerably in error. The results ¶ were :—

Using 18 stars : 1·38 and 2·09 sec., mean 1·73 sec.
Using 17 stars : 1·73 and 2·17 sec., mean 1·95 sec.
Using 16 stars : 1·73 and 2·75 sec., mean 2·24 sec.
Using 15 stars : 1·28 and 2·18 sec., mean 1·73 sec.

The results are somewhat discordant, but clearly indicate an Einstein value of 1·745 rather than the half value of 0·87 second.

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* H. N. Russell, M.N. R.A.S., lxxxi., p. 154 (1920).
† W. H. Pickering, Popular Astronomy, xxx., No. 4, p. 1 (1922).
‡ Kodaikanal Observatory Bulletin, p. 72 (1923).
§ C. A. Chant, Journ. Roy. Astr. Soc. Canada, xvii., p. 1 (1923).
‖ Smithsonian Report for 1919, p. 133.
¶ R. K. Young, Journ. Roy. Astr. Soc. Canada, xvii., p. 129 (1923).

Dr. W. W. Campbell of the Lick Observatory used a pair of 15-ft. cameras working at *f*36 and a pair of 5-ft. cameras working at *f*15*. The measurements of the plates taken with the 5-ft. cameras have not yet been completed, but the 15-ft. camera plates have afforded a decisive result. With exposures of about two minutes, the plates recorded in all 92 measurable stars, ranging from 4·3 to 10·8 photographic magnitude, the number of stars used on individual plates varying from 62 to 85 †. These plates give values of 1·80, 1·48, 1·85, 1·76 second, with a mean value of 1·72 second and a probable error of only 0·11 second. This result is little over one per cent. less than Einstein's predicted value of 1·745 second. Calculation of the precision index and hence of the probability integrals shows that the chance of the correct value being 0·87 second is less than one in a thousand.
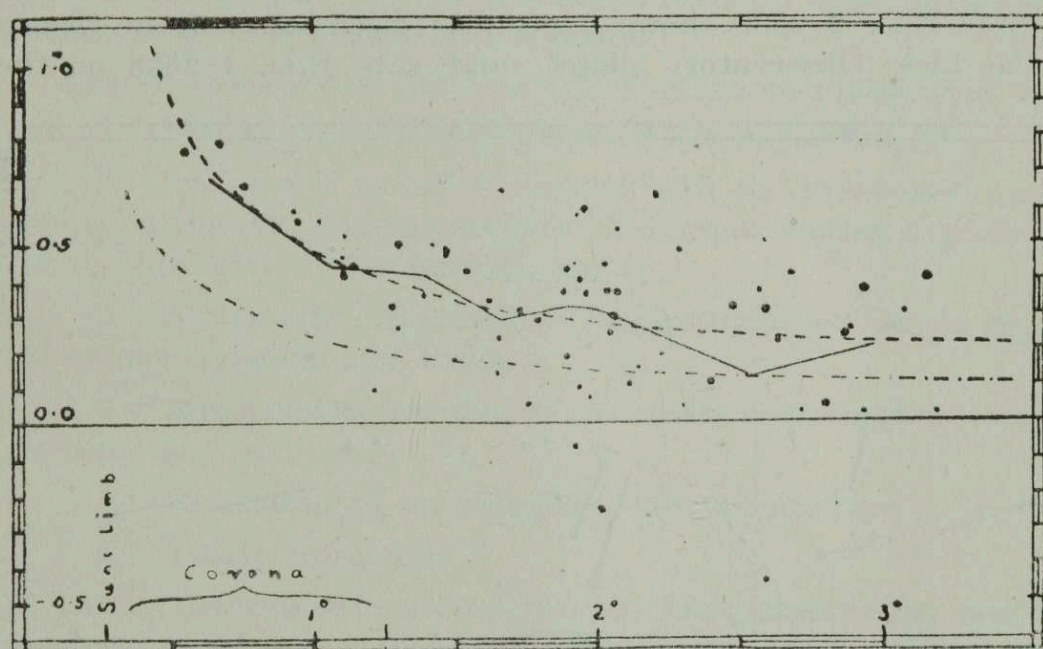

Fig. 1.   Radial Displacements of Eclipse Stars as a function of their angular distance from the sun's centre.

Fig. 1 shows the radial displacement of individual stars, and the irregular continuous line connects the group means of the weighted observed displacements. The dotted line represents Einstein's predicted values, and the chain line lower down in the diagram indicates the displacements which would be found on a Newtonian theory if light were subject to gravitation. It is to be noted that the Lick Observatory computations did not assume an Einstein term in the observed displacements. The displacements of the stars were measured, corrected for the effects of proper motion, annual parallax, differential refraction, aberration, and

* W. W. Campbell, Publ. Astr. Soc. Pacific, xxxv., p. 11 (1922).
† Lick Observatory Bulletin, p. 346 (1923).

inclination of the plate normal to the optical axis. In the measurements the displacements of the stars were taken relative to all those at distances exceeding two degrees. Having established from these relative displacements the existence of the Einstein effect, a correction was applied to reduce the relative displacements to absolute values.

Fig. 2 shows, magnified 3,000 times, the measured displacements of 50 of the 92 stars, viz., of those which appear on several plates and give fair images. Only the positions of the other stars are indicated. The dotted line indicates the farthest extent to which the corona can be traced on the negatives. The brightness of the corona prevented satisfactory observations of any stars within 15 minutes of the sun's limb in polar directions or within 50 minutes of the limb in equatorial directions.

Star B.D. 2·2509 shows a peculiar discrepancy from theory on the Lick Observatory plates, and star B.D. 1·2628 on the
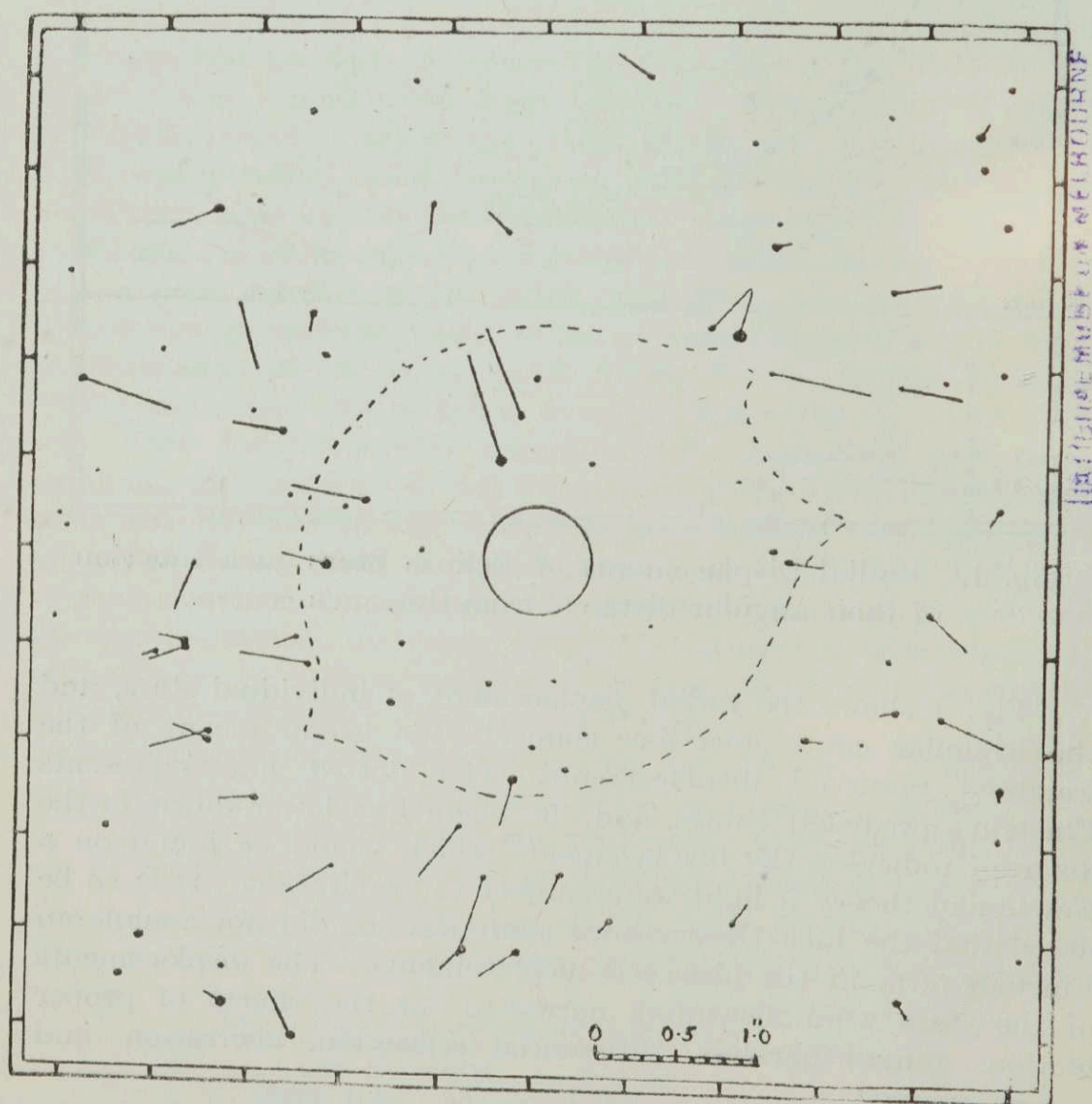

Fig. 2.   Observed Radial Displacements of Eclipse Stars.

Canadian plates. Thus for B.D. 2·2509 the Einstein prediction is + 0·02. The observed displacements are — 0·72 (Lick Obs.) and + 0·35 (Canadian). For star B.D. 1·2628 theory gives + 0·81, as compared with observed values + 1·46 (Canadian) and + 0·76 (Lick Obs.). As the discrepancies are not common to the plates of both expeditions, they must be due to some experimental or observational effect, such as local shrinkage of the plate film.

The Lick Observatory's photographic programme differed from that of the Canadian party in that a check star field (surrounding 70 Ophiuchi) was photographed superimposed on the test star field both on the eclipse plates E and on the comparison plates N. As this check field was far from the sun in all cases, its star images could not show a displacement between the E and N plates due to an Einstein effect. As a matter of fact no displacement of this kind was found, but there was a slight reversed effect in the case of stars nearer the centre of the plate.

Eclipse tests of the Einstein effect might be invalidated by—

    1.   Distortion of optical parts of the apparatus *.

    2.   Systematic errors in setting with the measuring microscope on the star images owing to the corona causing a gradation of the intensity of the background †.

    3.   Systematic distortion of the photographic film in drying after development and fixation ‡.

    4.   Abnormal refraction in the earth's atmosphere during totality §.

    5.   Refraction in an extended solar atmosphere ‖.

    6.   Yearly refraction ¶.

In the determinations made by the Lick Observatory and the Canadian party, error under the first source was reduced to a minimum by using equatorially mounted cameras and so obviating the necessity for coelostat mirrors. Errors under 2 were eliminated in the case of the Lick Observatory's measurements by use of the check star field, while the same device enabled errors under 3 to be estimated. The small reversed effect found with the check region stars superimposed on the central part of the eclipse plates is probably due to the more rapid drying and consequent shrinkage of the parts of the film blackened by the corona. Allowance for the effect increases the value of 1·72 second obtained for the Einstein constant to about two seconds **. Errors under 4 and

    * H. N. Russell, M.N. R.A.S., lxxxi., p. 154 (1920).
    † M. Wolf, Astr. Nachr., ccxii., p. 181 (1920).
    ‡ F. Ross, Ap. Journ., lii., p. 98 (1920).
    § A. Anderson, Nature, civ., pp. 354, 372, 393, 436, 468, 563 (1919–20).
    ‖ H. F. Newall, M.N., R.A.S., lxxx., p. 22 (1919), Observatory, xlii., p. 428 (1919), xliii., p. 145 (1920). W. Anderson, Astr. Nachr., ccxviii., p. 251, (1923).
    ¶ Courvoisier, Astr. Nachr., ccxi., p. 305 (1920).
    ** It is to be noted that this correction is obtained by extrapolation, and it should not be taken as indicating more than the nature and order of magnitude of the effect.

5 are extremely unlikely when the star images are sharp, when
the displacements vary closely in accordance with the Einstein
law, and when the law is obeyed equally well by stars viewed
through the corona and by stars appearing beyond its visible limits.
Courvoisier's yearly refraction effect is quite unknown for stars
near the sun.   An effect rising from zero at the sun's limb to about
0·4 second at a distance of two degrees or more would, when added
to the Einstein effect, bring theory and observation into still closer
agreement.